Defense Technical Information Center Compilation Part Notice

ADP013233

TITLE: Double Injection Currents in p-i-n Diodes Incorporating Self-Assembled Quantum Dots

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [9th], St. Petersburg, Russia, June 18-22, 2001 Proceedings

To order the complete compilation report, use: ADA408025

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP013147 thru ADP013308

9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Double injection currents in p-i-n diodes incorporating self-assembled quantum dots

A. E. Belyaev†, A. Patanè†, L. Eaves†, P. C. Main†, M. Henini†
and S. V. Danylyuk§
† School of Physics and Astronomy, University of Nottingham,
Nottingham NG7 2RD, United Kingdom
§ Institute of Semiconductor Physics, NASU, Kiev 03028, Ukraine

Abstract. We study p–i–n diodes incorporating InAs/AlAs self-assembled quantum dots (QDs) to probe the electron and hole levels of the dots. Comparative analysis of capacitance-voltage ($C-V$), current-voltage ($I-V$) and electroluminescence (EL) measurements shows that p–i–n structures could be successfully used as a quantum dots spectrometer.

Introduction

Among the structures proposed as quantum dots (QDs) spectrometers, devices with Schottky contacts [1] and unipolar structures [2] (i.e. n–i–n or p–i–p diodes) are those more frequently used. In contrast, p–i–n diode incorporating QDs have not been deeply investigated. In contrast to the case of Schottky diodes, the potential distribution over the intrinsic region (i) of a p–i–n diode is almost linear. This implies a simple procedure for converting an applied voltage to the energy shift of the QD states. Also, in contrast to unipolar devices, p–i–n diodes offer the possibility to investigate in the same device both the electron and the hole dot states. In this work, we present a study of bipolar transport in a p–i–n diode incorporating InAs/AlAs QDs. This study is carried out by a comparative analysis of capacitance-voltage ($C-V$), current-voltage ($I-V$) and electroluminescence (EL) measurements.

Experimental results and discussion

In our p–i–n diode, the composition of the layers in order of growth on a n^+-substrate is as follows: an n^+-doped $GaAs$ buffer layer ($n^+ = 4 \times 10^{18}\,\text{cm}^{-3}$); a 100 nm-thick n-doped GaAs layer ($n = 2 \times 10^{16}\,\text{cm}^{-3}$); an undoped, intrinsic region (i), which consists respectively of a 100 nm-thick GaAs layer, a 10.2 nm-thick AlAs barrier and a 60 nm-thick GaAs layer. The growth was completed by a p^+-doped GaAs layer ($p^+ = 2 \times 10^{18}\,\text{cm}^{-3}$). The QDs were grown in the middle of the AlAs barrier, by depositing 1.8 ML of InAs.

The $C-V$ and $I-V$ characteristics of the sample are shown in Fig. 1. The $C-V$ curve is characterized by two distinct regions, — low- and high-capacitance. The value of the capacitance in the first region is consistent with the value expected for a flat capacitor, with a distance between the capacitor plates equals to total base length of the structure, L. Sharp transition from the low- to the high-capacitance region occurs when the flat band regime is achieved and the electron and hole 2D layers form outside the AlAs barrier.

The formation of the 2D layers is also confirmed by the appearance of Shubnikov–de Haas-like magneto-capacitance oscillations vs. magnetic field, B, (at fixed voltage) for B applied parallel to the growth direction. The charge modulation arising in this case affects

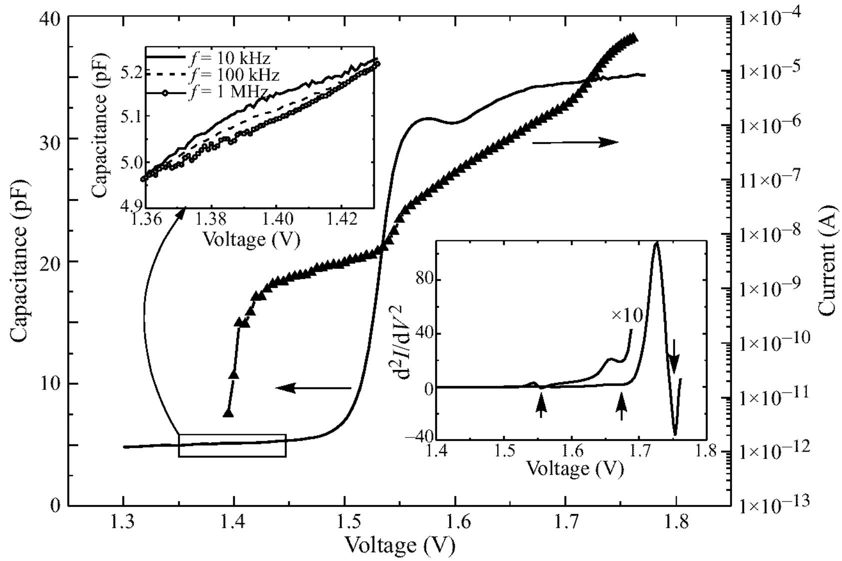

Fig. 1. Capacitance–voltage dependence measured at frequency of 10 kHz and zero magnetic field (left-bottom) and dc current–voltage characteristics (top-right) of the p-i-n diode. Upper inset: Capacitance curves near voltage 1.4 V for different frequencies of a modulating signal. Lower inset: the second derivative of current vs applied voltage.

the distribution of electric potential and screening length, and hence modulates the capacitance of the device. The fundamental field, $B_f = [\triangle(1/B)]^{-1}$, measures the electronic sheet density of 2DEG in the accumulation layer $n_s = 2eB_f/h$. Thus, extrapolation of fundamental field B_f dependence on applied voltage to zero-B_f value yields an information about voltage at which the flat band regime occurs. The obtained voltage value is close to GaAs band gap at 4.2 K – 1.512 eV.

In further, we will focus on the resonant features of the capacitance, which appear in both low- and high-capacitance regions. A wide bump is observed at 1.4 V for a frequency of 10 kHz (upper inset in Fig. 1). The current increasing is also observed in the $I-V$ curve within the same voltage region. We believe that this feature is caused by filling of impurity states located in i-region. This feature depends on the modulation frequency. With increasing frequency the amplitude of this feature becomes weaker and disappears for a frequency of about 1 MHz. This frequency dependence could be explained in the next way. Magnitude of the effect depends on number parameters — tunneling and emission rates for both electrons and holes as well as $e-h$ recombination rate. To reach equilibrium between impurity levels and emitter, a modulation signal frequency must be much lower than the thermionic emission rate. When frequency becomes considerably larger than emission rate the carriers cannot follow the measurement signal and do not modulate charge both at the edge of space charge region and at the point where the Fermi level crosses the impurity level.

The second feature appears at around 1.56 V in both the $C-V$ and $I-V$ curves. A sharp resonance at this point is clearly visible on the second current derivative presented in lower inset of Fig. 1. A wide bump followed by dip is observed on $C-V$ curve that correlates with sharp increasing of the current at the same bias voltage. We attribute these features to capture of holes onto the QDs. Assuming uniform voltage distribution, then

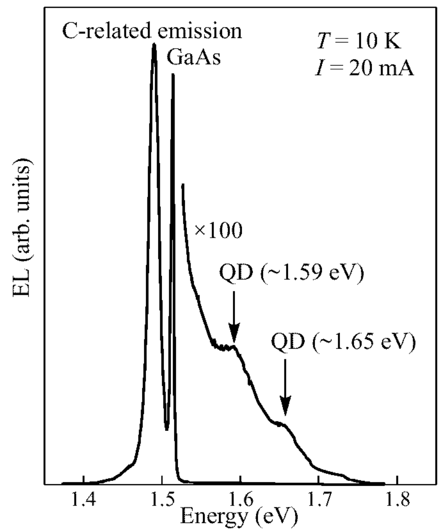

Fig. 2. EL spectrum of the QD structure measured at $T = 10$ K and $I = 20$ mA.

the leverage factor can be simply calculated for electrons (holes) as ratio $\frac{\lambda_{e(h)}+b/2}{\lambda_e+b+\lambda_h}$, where λ_e and λ_h are the quantum stand-off distances of the carriers in the accumulation layers formed to the left and right of the barrier b. The carrier sheet concentration, n_s, provides us with wavefunction stand-offs [3] ($\lambda_{e,h} \sim n_s^{-1/3}$). We obtain the leverage factor for high capacitance region equal to 0.33 and 0.67 for holes and electrons, respectively. Performing the procedure for QDs hole state, we estimate the position of ground QDs hole state at 15 meV beneath the top of $GaAs$ valence band.

Around the voltage of 1.67 V we observe a kink on $I-V$ curve that is reflected in $C-V$ dependence as increase of capacitance. The feature is more visible on the second derivative, d^2I/dV^2 and should be prescribed to the transport through the ground electron level of the QD. Using electron leverage factor for this voltage, we obtain the energy position of the ground electron state of the QD at 105 meV above GaAs band gap. Besides, there is noticeable increase of current in $I-V$ dependence at 1.71 V (Fig. 1). For that bias a probability of $\Gamma-X$ tunnelling strongly increases, that yields considerable contribution to the tunnel current.

To approve our model electroluminescence (EL) measurements were performed. Figure 2 shows the 10 K resulting EL spectrum of our device. The dot emission appears on the high energy side of the GaAs emission and it consists of two weak bands peaked at about 1.59 eV and 1.65 eV. The origin of these features should be the $e-h$ recombination via indirect exciton states that form at voltages far away the flat band condition. Really, at voltage bias exceeding 1.5 V the electron and hole 2D layers accumulate on outer sides of the barrier. The Coulomb attraction should promote the formation of spatially indirect excitons. However, the EL spectra were measured at 2 V when the $e-e$ interaction in 2DEG effectively suppresses the formation of indirect excitons. Moreover, we did not observe any manifestation of interplay between screening and exciton binding like that reported in [4], for similar device but without QD layer. If a feature in EL spectra at 1.59 eV is due the electron-hole recombination from the ground states of the dots, the energy gap between ground electron and hole QD state is 40 meV less, then value obtained from transport measurements. We assume, that in EL measurements, ground states of QD is affected by

Coulomb interaction between carriers and excitonic state forms. In this case corresponding transition energy could be considerably lower, especially with spatial 3D confinement. Thus, we obtain exciton binding energy of order of 40 meV. The next feature observed in the EL spectra 1.65 eV we attribute to the electron-hole recombination from the excited states of the QD bare exciton. The weak intensity of the dot signal is probably due to the presence of non-radiative recombination centers existing in the AlAs layers.

Conclusions

In conclusion, we have used the p-i-n diodes containing the layer of InAs quantum dots in an insulating region as spectrometer for probing electronic levels of QDs. Advantages of such devices for capacitance measurements are shown. It is shown that ground electron level of the InAs quantum dots in AlAs matrix reveals itself 105 meV above the GaAs conduction band edge, while the lowest hole level moves 15 meV downward the GaAs valence band edge.

Acknowledgements

This work is supported by EPSRC (UK) and Ukrainian Ministry of Education and Science. A.E.B. acknowledges the Royal Society for financial support.

References

[1] R. J. Luyken, A. Lorke, A. O. Govorov, J. P. Kotthaus, G. Medeiros-Ribeiro and P. M. Petroff, *Appl. Phys. Lett.* **74** 2486 (1999).
[2] P. M. Martin, A. E. Belyaev, L. Eaves, P. C. Main, F. W. Sheard, T. Ihn and M. Henini, *Solid State Electron.* **42** 1293 (1998).
[3] F. F. Fang and W. E. Howard, *Phys. Rev. Lett.* **16** 797 (1966).
[4] A. Parlangeli, P. C. Christisnen, A. K. Geim, J. C. Maan, L. Eaves, P. C. Main and M. Henini, *Phys. Rev. B.* **60** 13302 (1999).